10. USE OF COMPUTERS IN PHYSICS EDUCATION
INVITED PAPER

FIOLHAIS, Carlos
Physics Department and Center for Computational Physics
University of Coimbra
P- 3000 Coimbra - Portugal
tcarlos@hydra.ci.uc.pt
&
TRINDADE, Jorge Fonseca
Physics Department
High Education School for Technology and Management
P- 6300 Guarda - Portugal
alberto@hydra.ci.uc.pt

Abstract - **Physics is said to be a difficult subject. Among the reasons for the learner's difficulties, one has been subject to intense research: the naive conceptual framework in which students insist to explain the world around them. Nevertheless, there have been more questions arising than answers provided to solve these kinds of problems. We point out the role of computational techniques, namely Simulations, Multimedia, Telematics, Virtual Reality, and computer Based Labs which may deal with those difficulties and increase the learning success. We describe our ongoing experience in the field.**

10.1. PROBLEMS WITH PHYSICS LEARNING AND COMPUTER APPROACHES

Science learning, in particular Physics learning, is not an easy task. Two examples suffice to give an illustration of that. Portuguese final exams at the end of secondary studies show the lowest grade point averages in Physics and Mathematics. On the other hand, in various Portuguese universities, General Physics is considered by freshmen to be a very difficult course and statistics accumulated along the years show persistent negative results.

There is strong evidence all over the world that introductory Physics students in the usual university lecture courses are not learning the concepts necessary to a good understanding of the physical world. Moreover, students leave their courses with some fundamental misunderstandings of the physical world essentially intact: their learning of scientific facts remains in the classroom and has no later effect on their thinking [19-21]. Student performance does not seem to depend on whether students have or not taken physics courses in high school [20] and the ineffectiveness of university courses is independent of the apparent skills of the teacher.

Anyone interested in this problem should deal with two types of questions:

- ❑ how students learn Physics and Mathematics;
- ❑ how to use computers to improve learning.

These aspects are of course intimately related, *i.e.*, the best use of modern interactive media should be based on our best knowledge on the way students learn.

Alfred Bork and Seymourt Papert, a physicist and a mathematician, were pioneers in this type of approach.

Bork, in June 1978, in an address to the American Association of Physics Teachers, under the title "Interactive Learning", enounced a prophecy which has been fulfilled only partially [1]:

"We are at the onset of a major revolution in education, a revolution unparalleled since the invention of the printing press. The computer will be the instrument of this revolution. Although we are at the very beginning - the computer as a learning device in current classes is, compared with all other learning modes, almost nonexistent - the pace will pick up rapidly over the next 15 years. By the year 2000, the major way of learning at all levels and in almost all subject areas will be through the interactive use of computers."

According to Bork, some advantages of using computers in education are the following [2,3]:

- Interactivity. The computer allows every student to play an active role in the learning process, in contrast to the passive role of lecture and textbook formats. The student is no longer a spectator, but is an active participant in the learning process. There is a multiplicity of situations to be explored and this can be done at the user's discretion.
- Individual attention. Educators know that students are different. Not all students have the same backgrounds and not all students learn in the same way. However, many of our conventional approaches to education use a rigid procedure for all students and do not allow taking these differences into account. An advantage of the computer is that, with good software, it can individualize instruction. Furthermore, as all students do not learn at the same rate, different students need different times to go through the learning material. The computer also allows that.

These ideas helped to abandon an initial stage of computer use in education, in which computers were basically tutorial machines running software which was designed to "program" students according to some fixed scheme. Bigger interactivity and feedback were needed to respond to the modern pedagogical theories.

Another important factor in the advance of computer use in education was that computers quickly became more powerful, therefore more and more suitable to implement new ways of learning. They got more rapid central processing units, taking advantage of the enormous miniaturization, more memory, both central and backup, and all this was provided at less cost. Graphic capabilities have improved considerably, allowing for full animation, realistic three-dimensional images, etc. A landmark which helped to democratize computers was the appearance of the personal computer in the late seventies.

Some interactive computer environments may indeed help the student to correct his non-scientific preconceptions. These are usually naive but extremely persistent. A way of correcting a wrong mental model consists in allowing him/her to explore the model using a simulation and to contrast the results to the correct scientific model and to reality. These computer environments are usually richer if they have some characteristics of a play [25]. Computer games provide challenges, require mental skills and offer a quick feedback. In computer games the difficulty level is incremental, attracting always the player's interest, but never so much that he loses interest for being unable to reach the goals. In the best simulations there is a fragrance of the game: good programs invite the user to explore, to try new commands and menus, to go forward, in a word to win the "play".

Alfred Bork in the above mentioned speech said: *"Play is a way of gathering, under highly motivated circumstances, a variety of experiences, possibly even focused experiences. An experiential base is a vital ingredient in the learning process"*.

Some good computer programs for learning physics exist which are essentially computer games:

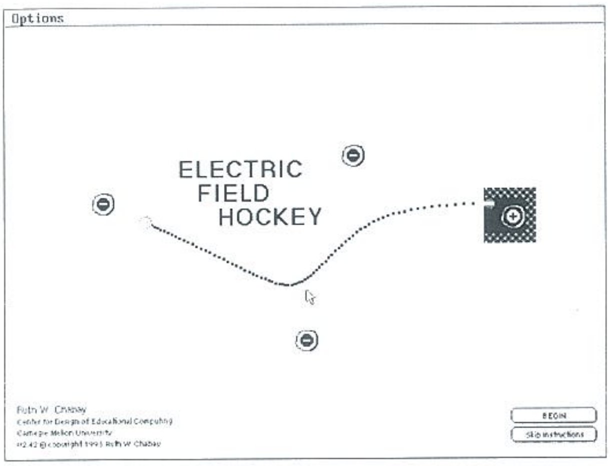


Figure 1 – The *Electric Field Hockey* software.

- *Electric Field Hockey*: a program written by Ruth Chabay, and published in the "Physics Academic Software" collection of the American Physical Society, teaches electric forces, putting a ball with a charge and driving it through conveniently applied forces (due to other electric charges) to a goal (Figure 1).

- *Graphs and Tracks*: a program of David Trowbridge, and also published by the American Physical Society, which is not only an educational game but also a good example of the contributions that educational research can make to the development of computer-based instruction [9]. The creation of *Graphs and Tracks* was motivated by the investigation of student's difficulties with motion graphs. Since it deals with misconceptions on Mechanics, a basic subject of Physics, it is worthwhile to examine it in more detail.

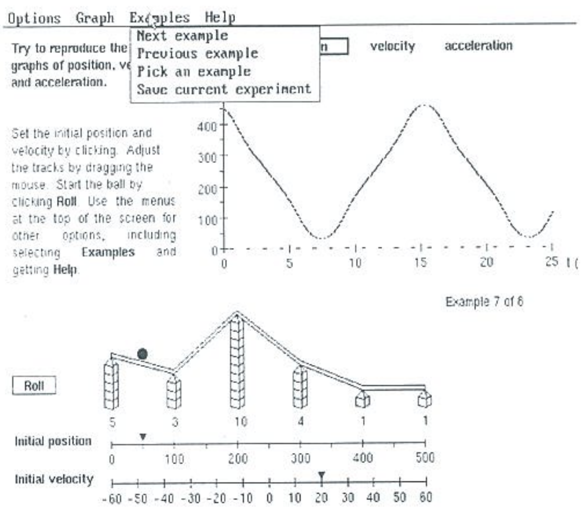


Figure 2 – One example of *Graphs and Tracks - Part I: From Graphs to Motion*.

The program is designed to help students to improve their ability to relate an actual motion to its various graphical representations. The physical system consists of a ball and tracks. The program includes a couple of example problems. For each problem, the computer presents a position versus time graph, a ball on a set of tracks, and two initial conditions (Figure 2). The student's task is to modify the track arrangement and initial conditions so that the ball will reproduce the motion represented in the graph. On the other option, the student should draw a graph corresponding to the motion along a given track (Figure 3).The original program made no judgment about whether the graph generated by the student was acceptable, nor did it provide any feedback to help the student decide which sections of the graph were improperly arranged. The student was responsible for detecting any errors, determining what changes were needed and deciding when the match was good enough to proceed to another example.On the current version there is a help screen that the student can request. If the graph generated by a proposed track arrangement fails to match the given graph, the help option can guide the student in searching for errors. Student's attention is directed, as

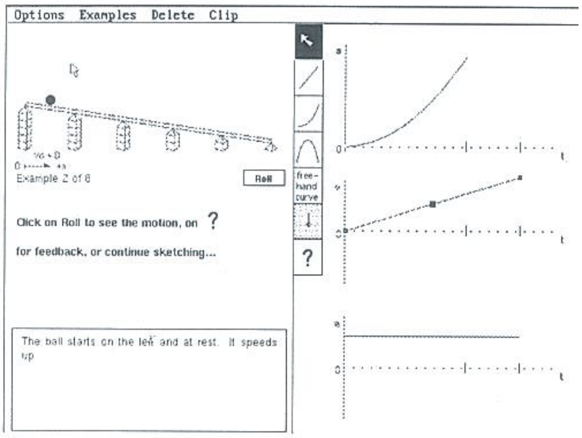


Figure 3 – One example of the Graphs and Tracks - Part II: From Motion to Graphs.

appropriate, to the choices of initial position and velocity, or the slope of a particular section of the track. The program assumes, therefore, some guiding role. The use of this kind of software is very instructive to deal with conceptual difficulties. The strategies that the students invoke may be observed with minimum influence by the investigator on the student's approach. Errors may be classified in typical categories.

Emergent computational tools and new developments in learning theories have contributed to changes in education. However, the results are still far from the best initial expectations. Different reasons may explain this phenomenon (*e.g.*, the reaction to change by school, which is a rather conservative institution). But it seems that we are still in the middle of the change process. Further progress should be made taking into account the rich accumulated experience. Let us sketch what have been the main ways of using computers in Physics, present our own experience in using these different ways, and, finally, write down conclusions and some prospectives.

10.2. DIFFERENT WAYS OF USING COMPUTERS

Today we may distinguish different ways of using computers for teaching and learning Physics [4,24]:

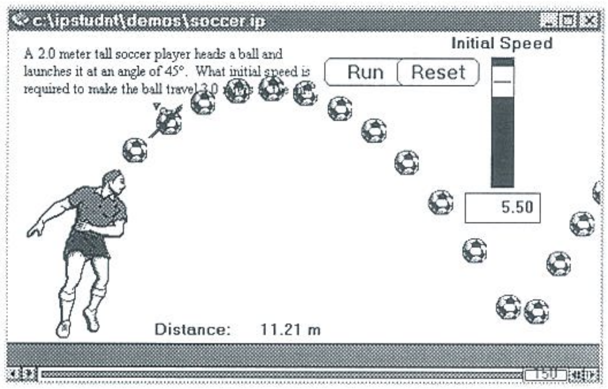


Figure 4 – Running the *Interactive Physics* software.

10.2.1. *Simulations*

This has been probably the most explored field. The above mentioned examples of computer games are basically simulations. So are many programs which have won the software contest organized by the journal "Computers in Physics" (a couple of them published by the "Physics Academic Software" initiative of the American Physical Society), the series *CUPS*, published in book format by John Wiley [7], the program *Interactive Physics* (Figure 4), a powerful simulation tool published by Knowledge Revolution, etc.

We talk about simulations when we run in the computer a model of Nature. Sometimes the word modelization is used when the emphasis is on building, *i.e.*, programming the model, while simulation is left for the situation when the model is considered a "black-box". This distinction is somewhat artificial and not always clear. Since the laws of Physics are expressed by differential equations, it is normally easy to implement a simulation for a given physical problem: this may be for instance the free fall of a stone, the orbital motion of a planet under the influence of one or more stars, and even the collision of two galaxies. However, simulations may also be made when we do not have a differential equation but an iterative relation: that is the case of the logistic map, a difference equation used in introductory studies of chaos.

Simulations should never entirely replace reality but are extremely useful when we have to study experiments which are impossible to do in practice (for being very expensive, very dangerous, very slow, very fast, etc.) Normally simulations offer the possibility for pedagogic exploration and sometimes, when the ludic element is present, give a reward for accomplishment some goal.

10.2.2. *Multimedia*

This modality is based on the concept of hypertext or, more in general, hypermedia. The word multimedia means that modules include a variety of elements, such as texts, images animations, simulations, and video clips [28]. The motto is "an image is one thousand words worth" so that the information should be as visual as possible. An hypertext module has several internal links and a reader does not need to follow a linear or sequential path through the module but, based on his experience and interests, may easily select those parts of the module that are of interest to him at the moment. Other links will enable users to move efficiently between different modules. Essential features of multimedia are interactivity and flexibility, *i.e.*, the possibility of entering commands and the ability to choose a path within the provided information. Since, according to some pedagogical theories, these factors are required for good learning, the educational advantages of multimedia have been widely advocated. The defenders of multimedia say that it is the convenient format for learning due to the fact that our brain processes information by free association of concepts in a intrinsically non-linear way. However, the sequential way, which still presides to the organisation of most courses, seems to be more adequate for systematising contents.

Multimedia may be on-line or off-line depending on the way that information is offered. A connection between these two supports is nowadays easily made. Multimedia off-line did not undergo the big explosion it has been announced, perhaps due to the enormous progress of the on-line format, which is mostly free. Anyway, these are several useful educative works: a nice example of the use of multimedia in Physics is the CD-ROM *Cartoon Guide to Physics* (Figure 5), based on the book with the same title by Larry Gonick and Art Huffman [8]. This disk may be used in Physics classes, although it is more recommended for extra-class activities. Like other multimedia products created for science learning, it

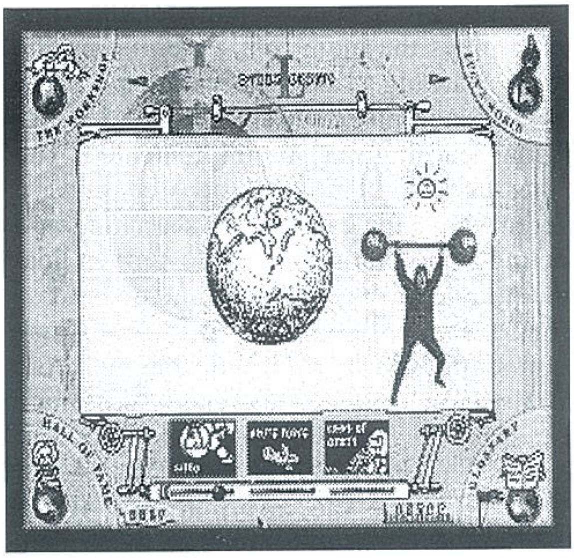


Figure 5 – Image of the *Cartoon Guide to Physics* CD-ROM.

includes several interactive simulations. Although the success of multimedia in science education has been restricted so far, its role in motivating students should not be disregarded. Even before the conceptual difficulties of the students emerge, lack of motivation for studying science may be the main cause for failure.

10.2.3. *Telematics*

The Internet, the network of all networks, has known a big success in the society in general and in schools in particular [25]. Its use for science teaching and learning shows still a big potential in spite of the amount of interesting work already done. Computer use in a network includes playing with simulations (these may be downloaded from the net or simply explored on-line if they have been written in the Java language), multimedia (HTML, the standard of the World Wide Web, is a multimedia language), and Virtual Reality (VRML is the standard for representing 3D objects or scenes on the Internet). Let us look at the way in which Internet is changing our teaching and learning styles.

In the prevailing education model, the teacher plays the main role, determining the pace of learning. Taking advantage of new technologies, more interactive and more personal learning may be implemented. The teacher should then help the student in a different way, for example in searching and selecting information relevant to a given goal in the middle of the enormous and disordered information oceans. Under these circumstances, his role will be no more central (one speaker at the stage and many listeners) to become peripheral (many speakers and many listeners). The teacher will no more be the information's single owner and provider to become an expert and consultant for discussing matters and solving problems. The World Wide Web became the biggest and the most lively of all libraries and the classroom walls have been demolished with the direct link to that source.

At the same time, the Internet represents a big step towards a bigger democratization of education, with equal opportunities being given to every student, independently of its geographical situation (if we are able to handle the known info-exclusion problem). Many courses exist on the Web and may be accessed by everybody from everywhere. A good example of Internet use for teaching Physics is the Java-based General Physics course at the Davidsson College, North Caroline, USA.

Sometimes, it is not only the aspect of the course but also the contents, which are new. Let us consider an example of revolution in learning contents which is being presented on the Web. One of the features of present education is the compartmentalization and specialization of instruction by departments and even by subgroups within departments. While this is understandable, and even necessary to some extent, it has the effect of obscuring the connections between different fields. For example, students in Mathematics classes often do not know how Mathematics is applied in engineering or science. At the same time, students in engineering or science

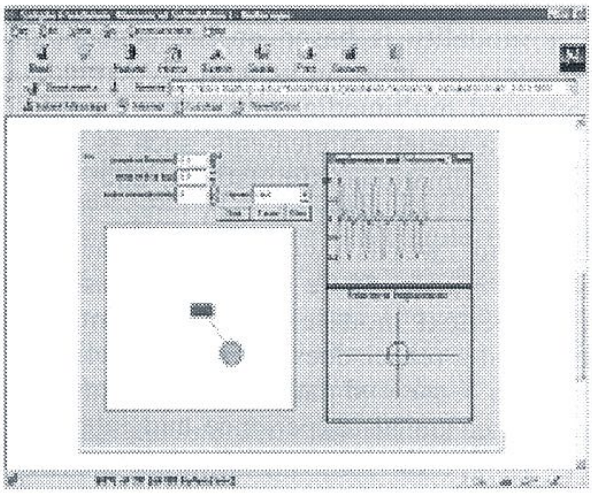


Figure 6 – A *Java* applet for studying the pendulum from the "Differential Equations and Mechanical Oscillators".

courses repeatedly fail to recognize that the

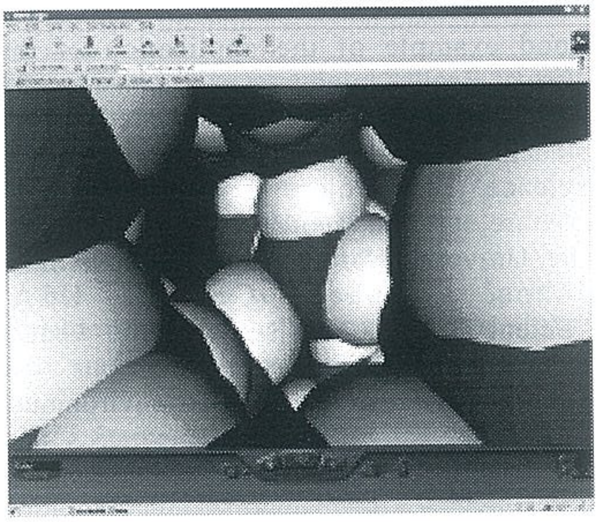


Figure 7 – Navigating through ice with the help of VRML from the "Virtual Water" project.

ideas and methods they learned in calculus or linear-algebra classes are what they need to solve problems they are bind.

Some universities have begun to explore other ways of organizing the education of scientists and engineers. For instance, the Rensselaer Polytechnic Institute, New York, USA, offers courses in what they call a "studio mode" [10]. For example, the "Mechanics, Linear Algebra, and the Bicycle" module is not designed to teach everything about mechanics, linear algebra, or bicycles. Instead, the module is meant to be a guided tour through some concepts of mechanics and related mathematical techniques, namely vectors, matrices, and sets of linear equations.

The module intends to draw on a student's interest in understanding how and why a bicycle is made the way it is. The module offers opportunities for a student to learn about mechanical and mathematical details, being its main theme is the link between mathematics and engineering in physical models. As a graphical demonstration, there is a Java applet that allows a student to create new bike shapes in two dimensions.

On the other hand, the "Differential Equations and Mechanical Oscillators" module is directed towards the study of mechanical oscillators. The first approach is analytical and conceptual. Assumptions based on engineering are used to reduce the actual physical system to a simple model. Then, application of the laws of Physics leads to a mathematical model, which consists of a system of one or more differential equations taken together with initial conditions. The oscillator module is divided into three parts. The first is devoted to an in-depth treatment of a mass attached to a vertically hung elastic spring; the second concentrates on the motion of a simple pendulum (Figure 6); and the third treats a spring-pendulum system in which the rod of the simple pendulum is replaced by an elastic spring.

VRML offers another possibility of using the Internet. It extends the usual HTML interface with the ability to visualize three-dimensional scenarios and interact with their basic elements. In areas like molecular science and solid-state physics, where the models need 3D representations, the new technique can be applied very effectively to improve understanding (Figure 7).

10.2.4. *Virtual Reality*

With Virtual Reality the focus of learning is placed in the conception of environments that allow students to interact with the computer with minimal restrictions [29]. According to Papert [26], a good learning environment requires free contact between the user and the computer. The reduction of the interface is precisely a necessary condition to immersive Virtual Reality. Two important implications result from immersion. First, there is a smaller distinction between the user (student) and the computer information (object of knowledge) [23]; second, immersion allows for a non-symbolic interaction with the environment.

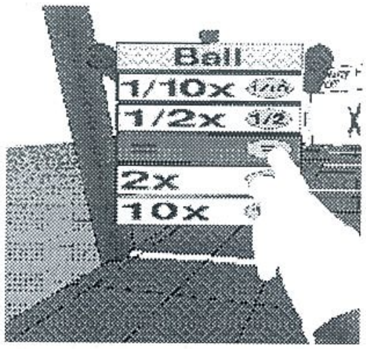
The main characteristics offered by Virtual Reality to education are immersion (most sensations come from the virtual environment), interactivity (free navigation, choice of referential, etc.) and manipulation (actions performed as in the real world). Virtual Reality brings together a set of characteristics that make it a unique technology as a learning means:

- Virtual Reality is a powerful visualization tool to handle 3D problematic situations.
- Virtual environments allow learning situations by trial and error that might encourage students to explore a wide choice of possible solutions.
- The student is free to interact directly with the virtual objects, allowing first-hand formulation and verification of hypothesis.
- The virtual environment can offer adequate feedback, allowing students to focus their attention on specific conceptual errors.
- Virtual Reality can collect and show complex data in real time.
- The immersive nature of Virtual Reality can endow students with extra capacities to retain information.

The "ScienceSpace" project [5, 27] is a good example of the application of the Virtual Reality in education. It consists of a series of virtual worlds designed to aid students in mastering challenging concepts in science. The project is a join research venture between George Mason University, the University of Houston, and NASA's Johnson Space Center, USA. "ScienceSpace" consists of three virtual environments (Figure 8 a-c):

- *NewtonWorld* provides an environment for investigating the kinematics and dynamics of one-dimensional motion.
- *MaxwellWorld* supports the exploration of electrostatics, leading up to the concept of Gauss' law.
- *PaulingWorld* enables the study of molecular structures via a variety of representations.

Another project, "Water on the Tap", is



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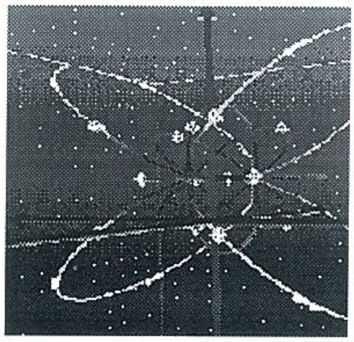

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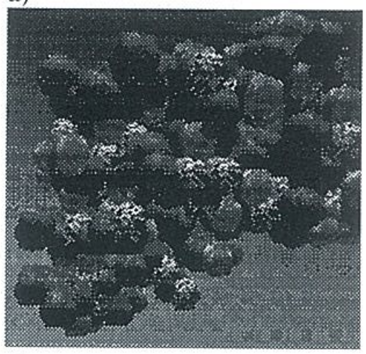

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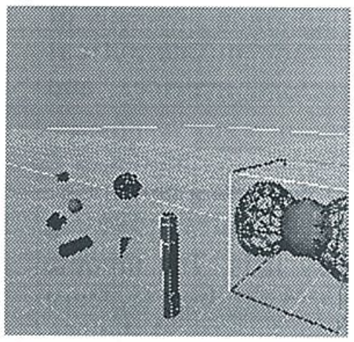

d)

Figure 8: Virtual environments for teaching physics: a) *NewtonWorld* from the "ScienceSpace" project; b) *MaxwellWorld* from same project; c) *PaulingWorld* from the same project; d) a virtual environment for the study of atomic and molecular structures, showing the $2p_1$ orbital from the project "Water in the Tap".

carried out at the University of Washington, Seattle, USA (Figure 8d).

10.2.5. *Computer-Based Laboratories*

Physics is an experimental science and the computer found already a place in the Physics laboratory. The richness of Computer-Based Labs and associated modeling tools could have a major impact on physics teaching and learning (Figure 9). We can use these tools to make Physics far less formidable for students with low mathematical abilities. We can use them to

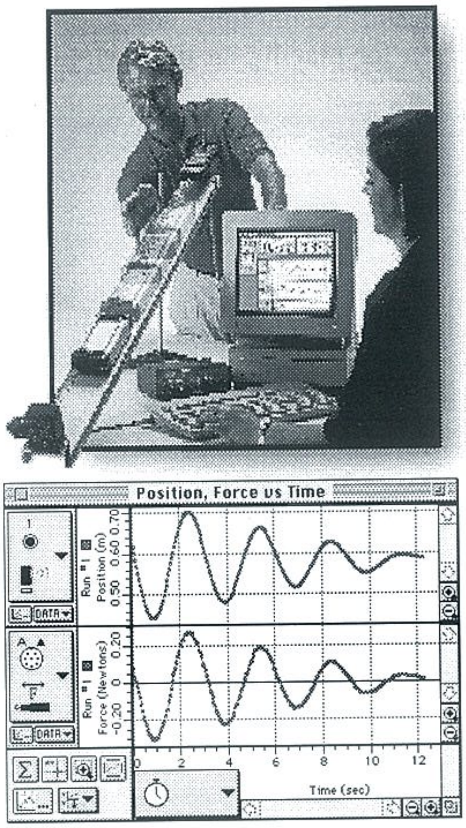

Figure 9 – The Pasco hard and software for a Computer Based Lab.

place more emphasis on intuition, and, at the same time, to give students the ability to solve complex problems.

Perhaps the most important possibility created by this technology is that it allows students to undertake their own original investigations. Much of what is wrong with science education is that students usually only learn about science: they do not participate in a meaningful way. Students at every level should have an opportunity to do real Physics experiments, to participate fully in learning new facts about the natural world. Hands-on participation provides not only a strong motivation but, more important, is the only way to give students an accurate understanding of science, whether their careers will lead them into science or not.

Learner-controlled explorations in the Physics laboratory with real-time measurements give students immediate feedback by presenting data graphically in a manner they can understand. Using sensors and software, students can simultaneously measure and graph physical quantities such as position, velocity, acceleration, force, temperature, etc. Those tools provide a mechanism for including in Physics teaching methods, which are found effective by educational research to deal with conceptual difficulties. The ease of data collection and presentation encourage students to become active participants in a process, which leads them to ask and answer their own questions. The real-time graphical display of actual physical measurements directly couples symbolic representation with the corresponding physical phenomena. Moreover, the comparison of real data with simulations is a very rich pedagogical tool.

10.3. Our Experience

10.3.1. *Simulations*

The Portuguese Physical Societies for Physics, Chemistry and Mathematics undertook in 1991 a common action - "Softsciences" - for producing and publishing educational software, mainly for the high-school but also for first year university courses.

In the following, we present a short description of some of our programs (see [11] for more information):

- *Kepler* (Figure 10), simulations of planetary systems with one star and one planet, two stars and one planet and one star and two planets.

- *Millikan*, a simulation of the famous experiment done by Robert Millikan to measure the electronic charge. The English beta demonstration program may be downloaded [13].
- *Relative*, a program on object motion in different, inertial or accelerated reference frames.
- *Periodic Table* (Figure 11), a very complete database containing information about the chemical elements. A reduced version of the periodic table in English is available on-line [17].

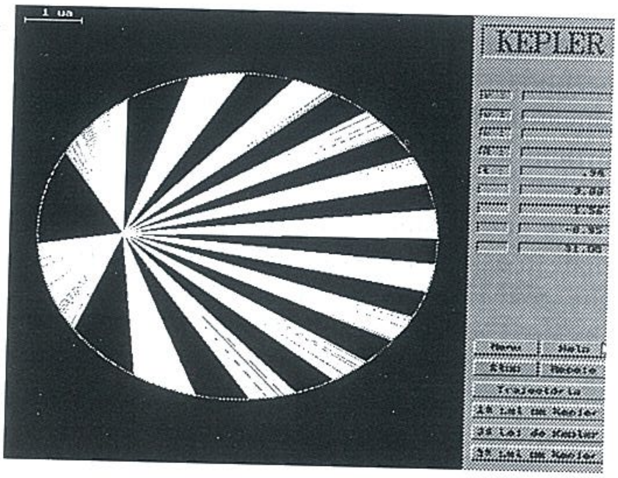

Figure 10 – The program Kepler from the "Softsciences" project.

- *Energy*, a strategy game which allows for the management of Earth's energy resources during the next 150 years.
- *Le Chat*, graphic illustrations of chemical equilibrium. The English demonstration version of the latter may be downloaded [12].
- *Throw!*, a simulation of javelin motion under the forces of gravity and air resistance.

All these programs have been included in a CD-ROM, named "Omniscience", published in 1997 and 1998 with the support of the Ministry for Science and Technology (Figure 12).

10.3.2. *Multimedia*

We have produced and included in our CD-ROM a multimedia edition of the *Periodic Table*, with large number of images, animations, videos, etc.

We have planned for a multimedia project based on the book "The Fun of Physics" [6].

10.3.3. *Telematics*

Recently, the Portuguese Ministry for Science and Technology has implemented an action for placing an Internet connected

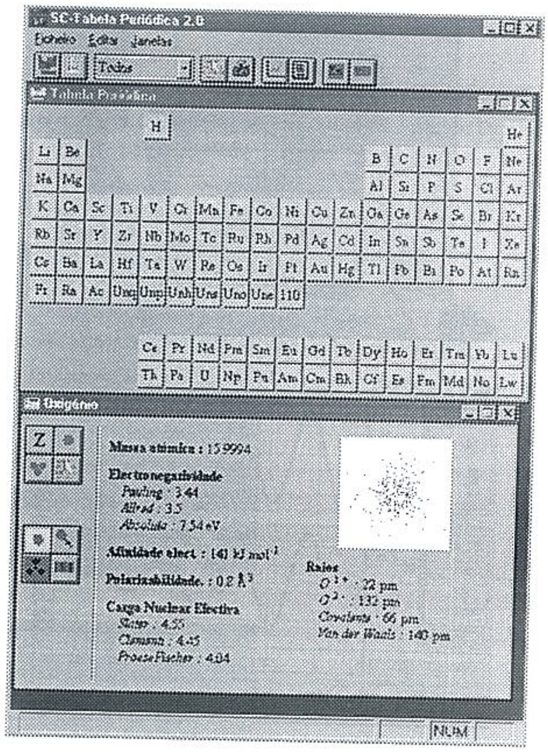

Figure 11 – An image of *Periodic Table* from the "Softsciences" project.

computer at the library of every Portuguese middle and high school.

We are providing educational contents that are available on line to schools and homes. A lot of information on "Softsciences" is on the Web. The oldest programs may be free downloaded. We have developed, as a framework for our materials, the

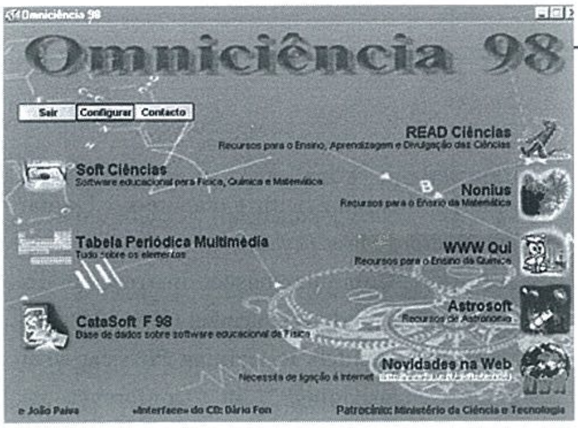

Figure 12 – The front page of the "Omniscience 98" CD-ROM.

"Omniscience" homepage, which is connected to the above-mentioned CD-ROM [18]. It encompasses all our software titles and educational materials.

One of our Web projects is called "READ Sciences" [14]: it includes science resources (*e. g.*, science experiments, a database with books on popular science, lists of the best science videos, etc.). Another of our pages is "Nonius" [15], honoring Pedro Nunes, a 16th century Portuguese mathematician: this, centered on Mathematics, offers not only a lot of links to the math educational world but also many items of our own. Our most recent feature is an educational resource Web page for Chemistry. That page contains an English section on chemical equilibrium [16].

10.3.4. *Virtual Reality*

Visualization of the electron orbital concept continues to challenge and intrigue chemical educators [22]. The orbital concept is crucial to the serious chemistry student who is exploring the nuances of atomic and molecular structures.

On the other hand, with the increased power of computing resources, it is more and more common to model systems atom by atom, moving each atom or molecule in response to the forces acting on it. From simulations like this one can better interiorize microscopic models and better understand a given substance's behaviour.

In collaboration with Centro de Computação Gráfica, Coimbra, Exploratório Infante D. Henrique, Coimbra, the Physics Department of Instituto Superior Técnico, Lisbon, and the High Education School for Technology and Management, Guarda, we are also developing the "Virtual Water" project, a virtual reality work applied to the learning of the Physics and Chemistry of water (Figure 13). The topics covered in the project go from the molecule geometry to the structures of the solid, liquid and gaseous phases, through the electronic density and the chemical bonding by hydrogen bridges. Atomic orbits are also included.

The project is being done in two phases: the first includes the visualization of the water molecule geometry, the hydrogen bonds, the molecular orbitals of water, the molecular electronic density and hydrogen wave functions. The second will include classical molecular dynamics of the solid, liquid and gaseous phases, phase transitions, and vibrational normal modes.

10.3.5. *Computer-Based Laboratories*

The Portuguese Physical Society, with support received from the Ministry of Science and Technology, is developing a project for introducing sensors and computers in Portuguese high-school laboratories. Up to now, 20 schools throughout the country has been equipped. Two workshops oriented by experts and regular support in loco provided by university students assured the necessary help for working with the new technologies.

10.4. Conclusions

After briefly referring to the conceptual difficulties in learning Physics, we have focused on the role of computer technologies to deal with them. We have classified the different uses of computers in Physics, besides the more trivial ones (like word processing, spreadsheet, etc.). Our division was schematic, since each type of use cannot be completely separated from the others. Simulations and Multimedia have already been much explored, in some cases achieving visible success for learning (namely some simulations with a game look) but also knowing some insuccess

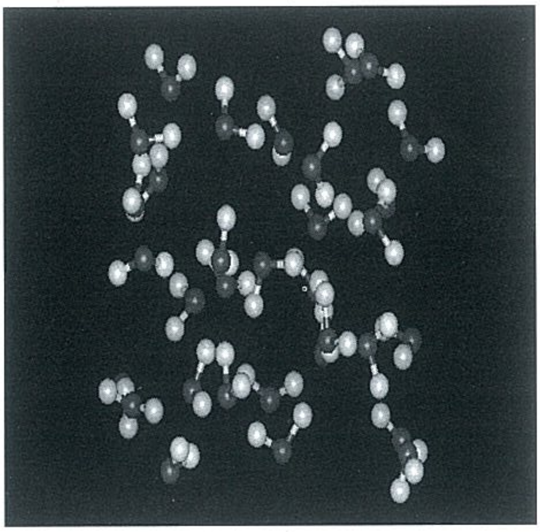

Figure 13 – A frame showing liquid water, from the "Virtual Water" project.

(Multimedia did not correspond to the hype). Telematics, Virtual Reality and Computers-Based Laboratories seem to be the more promising fields. They need to be further and better explored.

A word of caution is in order. We are not able to anticipate the future in this fast evolving domain. Probably new uses will be added to our list. For instance, nowadays the immense computer power of the Internet is being underused. Cooperative work with students participation taking advantage of that computer power to solve real scientific problems is a possibility that is starting to be explored. Science Education can only gain from being close to science.

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